ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 89 (2014) 1314 – 1320
Procedia Engineering
www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Experimental Investigation of Wave Scattering Effect of Pipe Blockages on Transient Analysis

H.F. Duan[a]*, P.J. Lee[b], J. Tuck[b]

[a]*Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Hom, Kowloon, Hong Kong*
[b]*Department of Civil and Natural Resources Engineering, The University of Canterbury, Private Bag 4800, Christchurch, New Zealand*

Abstract

This paper investigates experimentally the wave scattering effect of rough blockages in the pipeline and its impacts on the transient analysis for pipe systems. Two experimental configurations of rough blockages (hard gravels and fibrous materials) are considered in this study to examine the wave scattering effect on transient wave propagation. The results obtained in the experiments are used to validate and verify the findings of previous numerical and analytical studies. The results of this study can provide fundamental understanding and profound implications to practical applications such as transient-based pipe system design and pipe blockage detection.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Experimental verification; pipe blockage; transient analysis; wave scattering; wave propagation

1. Introduction

Random variations in the diameter (i.e., rough blockages) of fluid conveyance pipelines with respect to length develop with age are due to many practical factors such as bio-film build up, corrosion and deposition. Such random variations commonly occur in urban water pipe systems such as drainage pipes, crude oil lines, and arterial systems. From the perspective of steady flow in water supply systems, the random variations of rough blockages cause additional energy losses and, thus, requires more pumping. From the perspective of unsteady flow, random variations in pipe diameter by rough blockages result in random scattering of water hammer waves. Pressure waves propagating in such systems could be scattered (reflected and attenuated) randomly by the rough and irregular blockages in pipes.

* Corresponding author. Tel.: +852-34008449; fax: +852-23346389.
E-mail address: hf.duan@polyu.edu.hk

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.445

The phenomena of wave scattering in water piping systems and its implication to the structural integrity and robustness of such systems so far are not well understood.

Nomenclature

A	cross-sectional area of pipe
a	wave speed
B	amplitude of transient pressure trace
D	pipe diameter
k	wave number
L	pipe length
P	pressure
Re	Reynolds number
RA	relative importance
WS	contribution of wave scattering
t	time
x	distance
α	spatial correlation factor of rough blockage along pipeline
ω	wave frequency
μ_A	mean of cross-sectional area of rough blockage
$\zeta(x)$	random function with regard to distance
σ_A	standard deviation of cross-sectional area of rough blockage
λ_r	wave damping factor
λ_i	wave shifting factor
δ_A	coefficient of variation of cross-sectional area

Wave scattering has been commonly studied in other water systems and in particular in shallow water flows where water wave propagation through a channel with irregular bed topology is of significant interest [1]. Experimental results for such cases together with some theoretical considerations are investigated and discussed in [2, 3]. The results in these studies indicated that, with the existence of the random inhomogeneities of channel bottom elevations, the amplitude of the wave decreases rapidly along the channel. Propagation of slowly modulated waves in random media is studied in [4, 5]. The effects of three modulations: dispersion, weak nonlinearity and random inhomogeneities have been analyzed in that study using the method of multiple scales. Their study showed that in the linear case randomness of the sea bottom leads to exponential attenuation of the wave in space.

In pipe flows, there have very little studies on the wave scattering phenomenon in the literature. While instead, past studies on pipe blockages are usually treated as regular blockages (e.g., [6, 7, 8]) or inner wall roughness represented by different friction factors (e.g., [9, 10]). The simplification of the blockage as uniform constriction of the flow cross-section area or more increases in pipe wall roughness neglects the complex interaction that is likely to occur in reality. The current models and theory are unable to replicate transient response in the field and often artificial adjustments of friction factors, wave speed, and pipe material visco-elasticity are required to achieve the replication of the measured results (e.g., [7, 9, 11, 12, 13, 14]). These adjustments are non-physically based and do not reflect the true nature of the wave behaviors within the pipe.

Recently, a study in [15] has demonstrated through analytical and numerical analysis that scattering and superposition of pipe fluid transients in pipes with irregular blockages causes the wave envelope to attenuate rapidly along the pipeline. Their study also showed that the increased attenuation of the wave envelope is caused by the redistribution of energy in the temporal and spatial domains and not a result of energy dissipation. The assumption of small blockage severities is made in that study for the analytical derivation based on the multi-scale perturbation method, which needs further validations and analysis for its validity and accuracy.

This paper is aimed to experimentally validate and verify the analytical and numerical results of wave scattering developed in the previous study of [15]. The detailed laboratory experiments on specially built rough and irregular blockages are conducted for investigating the wave scattering effect in transient laminar pipe flows. Further results analysis and discussion are conducted in the end of the paper.

2. Analytical results of wave scattering

The analytical analysis in [15] was conducted based on the one-dimensional (1D) water hammer equations ([16]). A random variation of pipe cross-sectional area was adopted to represent the rough blockage situation in pipes as follows:

$$A(x) = \mu_A[1 + \varepsilon\zeta(x)] \tag{1}$$

where: A is the mean of pipe cross-sectional area; $\zeta(x)$ characterizes the random function of pipe cross-sectional area and is assumed to be of zero mean and be of standard deviation of σ_A.

By applying the multiple scale analysis, the solution of the wave envelope evolution during propagation through an irregular blockage was derived in [15] as,

$$B = B_0 e^{-\lambda x} = B_0 e^{-\lambda_r x} e^{-i\lambda_i x} \tag{2}$$

where $B = B(x)$ = amplitude of wave envelope along the pipeline; B_0 = amplitude of the incident wave; $\lambda = \lambda_r + i\lambda_i$, and $\lambda_r = \alpha k^2\delta_A^2/(\alpha^2 + 4k^2)$ = wave damping factor, $\lambda_i = -k\alpha^2\delta_A^2/2(\alpha^2 + 4k^2)$ = wave phase (frequency) shifting factor; δ_A = coefficient of variation (COV) of the pipe cross-sectional area which quantifies the irregularity of the blockage,, and $\delta_A = \sigma_A/\mu_A$; k = incident wave number and $k = \omega$/a, where ω is wave frequency and a is wave speed; and α = a factor that correlates inversely with the average length of sections within of the blockage of constant diameter (L_b), where $L_b \sim 1/\alpha$ and describes the spatial variability of the blockage. The result of Eq. (2) clearly indicates that the wave envelope exponentially decreases with longitudinal distance (x) or equivalently with the wave time (i.e., $t = x/a$). In other words, the wave is scattered and localized by the random inhomogeneities of pipe cross-sectional area along the pipeline. The validity range and accuracy of the analytical results are validated and discussed through experimental tests in the following sections of this paper.

3. Experimental Setup and tests

The experimental testing system consists of an upstream pressurized water tank, pipeline, and downstream valve (discharge tank), as shown in Fig. 1, which was constructed and tested in the hydraulics laboratory of the University of Canterbury, New Zealand. The total length of the pipeline (L_0) is 41.53 m and is divided into three sections, where the initial and last sections are uniform pipes with fixed diameter of 73.2 mm, while the middle section is a specially constructed irregular blockage section. Two types of rough blockages are considered in this study: one is made by fibrous material and the other is hard gravels, with both blockages imposing irregular changes to the pipe cross sectional area. The two different blockages are expected to cover two common types of blockages encountered in pipeline systems, with the fibrous material representing irregular blockages formed from fibrous tree roots and the hard gravels representing irregular blockage from pipe wall corrosion and deposition. The parameters and system settings for two types of blockages are shown in Table 1 (named tests no. 1 and no. 2 in the table).

Pressure waves are generated by the fast closure of the end valve from an initially fully open state. The transient pressure data are collected by four pressure transducers with sampling frequency of 20 kHz, which are located at #1, #2, #3 and #4 along the pipeline as shown in Fig. 1. The range of initial Reynolds number ($\boldsymbol{Re}_0$) for the tests are listed in Table 1, which indicate the experimental tests used in this study are within laminar or low turbulent flow regimes ($\boldsymbol{Re}_0$<4000). The tests were kept within this low Reynolds number range for two reasons: (1) to reduce the influence of the roughness height in the irregular blockage section on the quasi-steady friction factor; and (2) to accurately simulate the unsteady friction effect by the analytical model in [17]. Note that the diameter of rough blockage (D_b) shown in Table 1 is the average diameter of the blockage section, and the COV of pipe cross-sectional area of rough blockage section (δ_A) is determined from the maximum and minimum values (A_{max} and A_{min}) measured along the pipeline and by considering a uniform distribution of the flow area, i.e., $\delta_A = (A_{max} - A_{min})/2\sqrt{3}A_b$ with $A_b = \pi D_b^2/4$ ([18]).

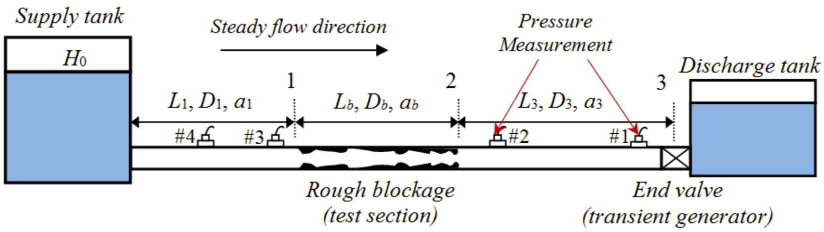

Fig. 1. Sketch of laboratory experimental testing system

Table 1. Settings for experimental testing system

System / test	*Blockage material*	*Uniform pipe sections*			*Blockage section*			***Re₀*** *(×10³)*
		L_1 (m)	L_3 (m)	D_1 (=D_3) (mm)	L_b (m)	D_b (mm)	δ_A	
no. 1	Fibrous	15.53	20.41	73.2	5.59	62.2	0.056	2.2~2.7
no. 2	Hard gravels	15.58	20.41	73.2	5.54	59.3	0.073	2.5~3.2

4. Results analysis and discussion

Two tests in Table 1 are conducted and used to investigate: (1) the transient wave envelope attenuation by wave scattering effect by rough blockages in pipes; and (2) the effect of different irregular blockage materials on the wave scattering. The measured transient responses in the time domain are plotted in Figs. 2(a) and 2(b) for tests no. 1 and no. 2 respectively, where the vertical coordinate is nondimensionalized transient pressure (ΔP_t, i.e., the transient part of the pressure relative to steady state) by the corresponding maximum value in the studied time domain (ΔP_{max}). For comparison the results of blockage-free (uniform pipeline) are also shown in the same figures. For comparison, the result of blockage-free is also plotted in the same figure. The comparative results in Fig. 2 show clearly the attenuation of the transient envelopes with time for both cases. For clarity, the envelopes of the measured responses are extracted and plotted in Figs. 3(a) and 3(b) for the two tests respectively. The relative amplitude (denoted as "*RA*" in the following figures in this study) on the vertical axes is defined by the wave peak amplitude in each period normalized by each first wave peak amplitude, and the peak number on the axial coordinate represents the period number of transient signals. The results of Figs. 3(a) and 3(b) show that both rough blockage materials induce the clear attenuations of the wave envelope with time.

To examine the wave scattering effect on transient analysis and its relative importance to friction damping, it is necessary to conduct the numerical simulations with considering the total friction effects (quasi-steady and unsteady) for the above two tests. The 1D water hammer models coupled with friction formulas are used in this study for this purpose ([16, 19]). In the numerical simulations, the rough and irregular blockage sections are approximated as uniformly constricted pipe sections, where the section is assumed to have the same constricted diameter. This is an approach commonly used in previous studies (e.g., [6, 7, 8]). As a result, no wave scattering effect exists within the numerical results. With this approximation, the wave scattering effect of rough and irregular blockages concerned in this study is then highlighted through a comparison between numerical results and measured data. It is again noted that all tests in this study are within the laminar or very low turbulent flow regimes. Therefore, the friction effect in the numerical simulations in this study is represented by the Darcy-weisbach equation for laminar quasi-steady friction ([16]) and Zielke's model for unsteady friction ([17]). Through calibration, the wavespeed for the uniform pipe sections is 1180 m/s, and the average wavespeed of the rough blockage section are estimated at 1240 m/s and 1285 m/s for the fibrous and hard gravels materials respectively.

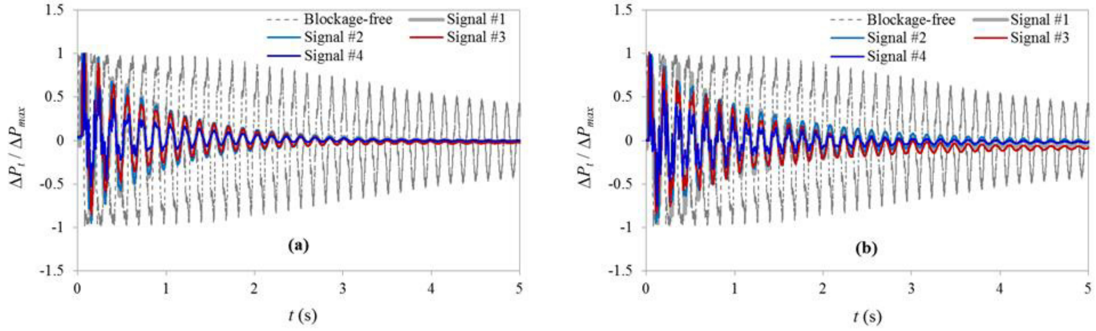

Fig. 2. Measured results of transient wave responses for tests no.1 and no. 2: (a) system no. 1 with fibrous material; (b) system no. 2 with hard gravels material

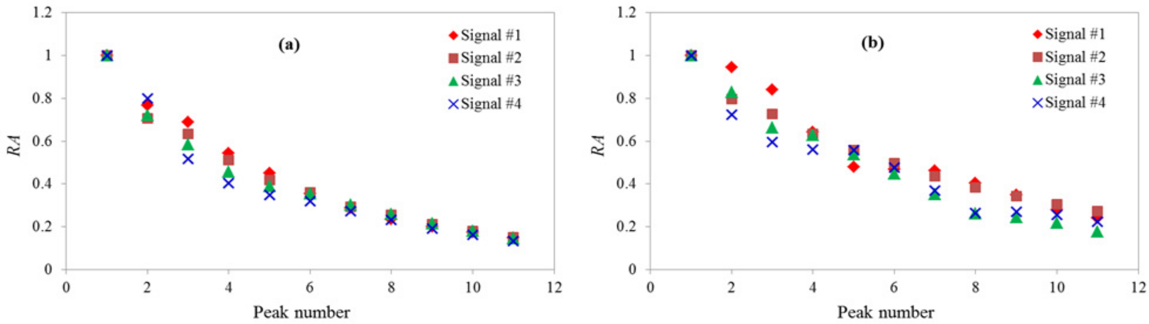

Fig. 3. Extracted envelopes of measured transient responses for tests no.1 and no. 2: (a) system no. 1 with fibrous material; (b) system no. 2 with hard gravels material

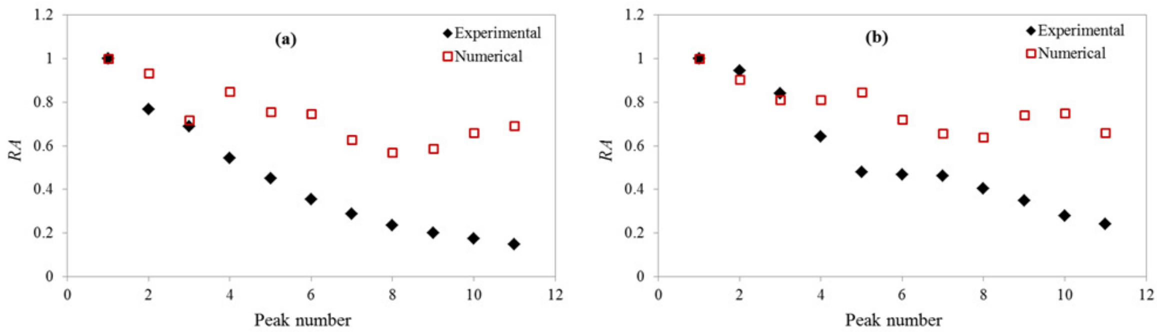

Fig. 4. Measured and numerical transient wave envelops at the test location #1s for tests no. 1 and no. 2

For simplicity, only the signal at test location #1 in the system of Fig. 1 is used for investigation in the following analysis. Other measured signals for each test can be analyzed by the similar procedure in this study and analogical conclusions can be obtained. The numerical and experimental results of the wave envelope are plotted in Figs. 4(a) and 4(b) for these two test signals, respectively. Both results clearly demonstrate the remarkable difference between the experimental data and the numerical results, indicating that the wave envelope attenuation in the rough blockage systems cannot be accurately represented by the previously used uniform and irregular blockage treatment with friction damping effect only. Therefore, the wave scattering effect of the random wave reflections and transmissions by rough and irregular blockages may have significant influences on the transient wave envelope attenuation.

To accurately represent the importance of wave scattering effect, the contribution of wave scattering to the wave envelope attenuation is defined in this study by the difference between the numerical and experimental results of envelope attenuation normalized by the total attenuation, mathematically as,

$$WS(\%) = \frac{(RA)_n - (RA)_e}{1-(RA)_e} \times 100 \tag{3}$$

where, WS = contribution of wave scattering effect; RA = relative amplitude of wave envelope; subscripts "n" and "e" = numerical and experimental results respectively. Based on Eq. (3), the contributions of wave scattering effect to the wave envelope attenuation for the two tests are calculated and plotted in Fig. 5 for the comparison of the two inspected systems. The results of Figs. 3 through 5 indicate the significant contribution of wave scattering effect to the wave envelope attenuation in pipe fluid transients. Particularly, the overall results show that the contribution of wave scattering effect in the first 2~3 wave cycles is relatively smaller than the total friction damping effect, but thereafter becomes progressively important and dominant to the wave attenuations (i.e., > 50%).

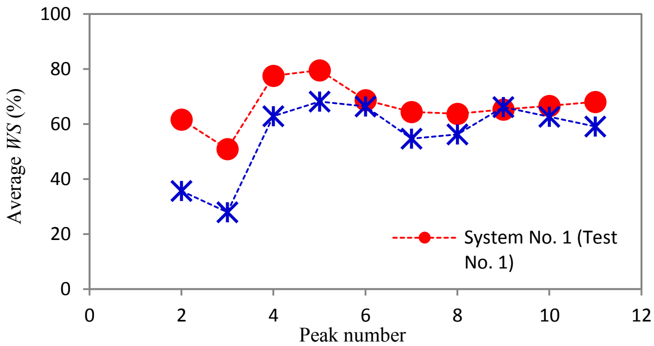

Fig. 5. Average contribution of wave scattering effect to wave envelope attenuation for different rough blockage materials

Based on the results and findings of this study, the practical implications include: (1) the wave scattering effect of rough and irregular pipe blockages may affect the design of pipe systems under transient conditions, especially in the aged/old pipelines. The random reflections and superposition of wave scattering could result in the extremely high and low pressure head in certain parts of pipe systems, which causes the design schemes of system strength from their initial new states may become overestimated or underestimated for some sections of the pipe system. (2) The significant amplitude attenuation and phase shifting of transient wave responses from the wave scattering effect may cause the inaccuracy or failure of transient-based pipe defect detection methods which are currently developed from the models and theory with excluding the wave scattering effect. (3) Wave scattering effect becomes critical for the formulation and identification of different transient models, such as unsteady friction and visco-elasticity models, which are usually validated and calibrated through the measured data of pressure wave attenuation and reflections from practical systems. Thus, they may be wrongly represented and explained if the potential wave scattering effect is not considered or not well included in the analysis.

5. Summary and conclusions

The paper investigates experimentally the wave scattering effect of rough pipe blockages on the transient wave propagation and analysis in pipelines under laminar transient flow conditions. The laboratory experiments are carried out and used in this study to validate and verify the analytical expression developed in the previous study for the wave scattering in rough blockage pipes. Two different types of rough blockage materials with different blockage severities and spatial correlations are constructed and adopted for the experimental investigation. The 1D numerical simulations coupled with quasi-steady and unsteady friction models are conducted to examine the difference between the wave scattering induced wave envelope attenuation and friction damping. The results show that the random wave reflections and superposition of wave scattering effect due to rough blockages cause the wave envelope attenuations in both spatial and temporal domains in the pipeline system. Moreover, the wave scattering contribution of wave envelope attenuation in the two inspected rough blockage systems of this study is smaller than the friction damping effect in the first 1~3 wave cycles, but thereafter it becomes progressively dominant and significant (i.e., comparable to or even more significant than the friction damping contributions). The comparison of measured data and numerical simulation as well as analytical results indicates the validity and accuracy of the previously developed analytical solution to represent the wave scattering in the rough blockage pipelines under the condition of small blockage severities (e.g., δ_A<10%). The results and findings of this study indicate that wave scattering effect of rough blockages may influence the transient flow modeling, design and analysis as well as the transient-based defect detection in practical engineering systems, especially in the aged pipe systems.

Acknowledgements

This research was financially supported by the research grants of the Hong Kong Polytechnic University (HKPU) under projects no. 1-ZVCD and no. G-UC73; and by the Royal Society of New Zealand, Marsden Grant UOC-M1153 of the Brian Mason Trust Fund (NZ).

References

[1] M. Dolan, R.G. Dean, Multiple long shore sand bars in the Upper Chesapeake Bay, Estuarine, Coastal and Shelf Sciences, 21 (1985) 721–743.
[2] M. Belzons, P. Devillard, F. Dunlop, E. Guazzelli, O. Parodi, B. Souvillard, Localization of surface waves on a rough bottom: theories and experiments, Euro phys. Letters, 4 (1987) 909–914.
[3] P. Devillard, F. Dunlop, B. Souvillard, Localization of gravity waves on a channel with random bottom, J. Fluid Mech., 186 (1988) 521–538.
[4] C.C. Mei, J.H. Pihl, Localization of nonlinear dispersive waves in weakly random media, Proc. R. Soc. Lond. A, 458, 2002, 119–134.
[5] C.C. Mei, M. Stiassnie, D.K.P. Yue, Theory and applications of ocean surface waves, part 1: linear aspects, World Scientific, Singapore, 2005, 220–284.
[6] H.F. Duan, P.J. Lee, M.S. Ghidaoui, Y.K. Tung, Extended blockage detection in pipelines by using the system frequency response analysis, J. Water Resour. Plann. Manage., 138 (2012) 55–62.
[7] H.F. Duan, P.J. Lee, A. Kashima, J.L. Lu, M.S. Ghidaoui, Y.K. Tung, Extended blockage detection in pipes using the frequency response method: analytical analysis and experimental verification, J. Hydraul. Eng., 139 (2013) 763–771.
[8] S. Meniconi, H.F. Duan, P.J. Lee, B. Brunone, M.S. Ghidaoui, M. Ferrante, Experimental investigation of coupled frequency and time-domain transient test-based techniques for partial blockage detection in pipes, J. Hydraul. Eng., 139 (2013) 1033–1040.
[9] G. Ebacher, M. Besner, J. Lavoie, B. Jung, B. Karney, M. Prévost, Transient modeling of a full-scale distribution system: comparison with field data, J. Water Resour. Plann. Manage., ASCE, 137 (2011) 173–182.
[10] M.L. Stephens, Transient response analysis for fault detection and pipeline wall condition assessment in field water transmission and distribution pipelines and networks, PhD Thesis, The University of Adelaide, South Australia, 2008, 220–311.
[11] D. McInnis, B.W. Karney, Transients in distribution networks: field tests and demand models, J. Hydraul Eng., 121 (1995) 218–231.
[12] S. Meniconi, B. Brunone, M. Ferrante, C. Massari, Potential of transient tests to diagnose real supply pipe systems: what can be done with a single extemporary test, J. Water Resour. Plann. Manage., 137 (2011) 238–241.
[13] M. Stephens, M. Lambert, A. Simpson, Determining the internal wall condition of a water pipeline in the field using an inverse transient, J. Hydraul. Eng., 139 (2013) 310–324.
[14] H.F. Duan, Y.K. Tung, M.S. Ghidaoui, Probabilistic analysis of transient design for water supply systems, J. Water Resour. Plann. Manage., 136 (2010) 678–687.
[15] H.F. Duan, J.L. Lu, A.A. Kolyshkin, M.S. Ghidaoui, The effect of random inhomogeneities on wave propagation in pipes, Proceedings of the 34th IAHR Congress, Brisbane Australia, June 26 – July 1, 2011.
[16] E.B. Wylie, V.L. Streeter, L. Suo, Fluid transients in systems, Prentice Hall, Inc. Englewood Cliffs, New Jersey, 1993.
[17] W. Zielke, Frequency-dependent friction in transient pipe flow, J. Basic Eng., 90 (1968) 109–115.
[18] Y.K. Tung, B.C. Yen, C.S. Melching, Hydrosystems engineering reliability assessment and risk analysis, McGraw-Hill Company, Inc., New York, 2006.
[19] M.S. Ghidaoui, M. Zhao, D.A. McInnis, D.H. Axworthy, A review of waterhammer theory and practice, Appl. Mech. Revs, 58 (2005) 49–76.